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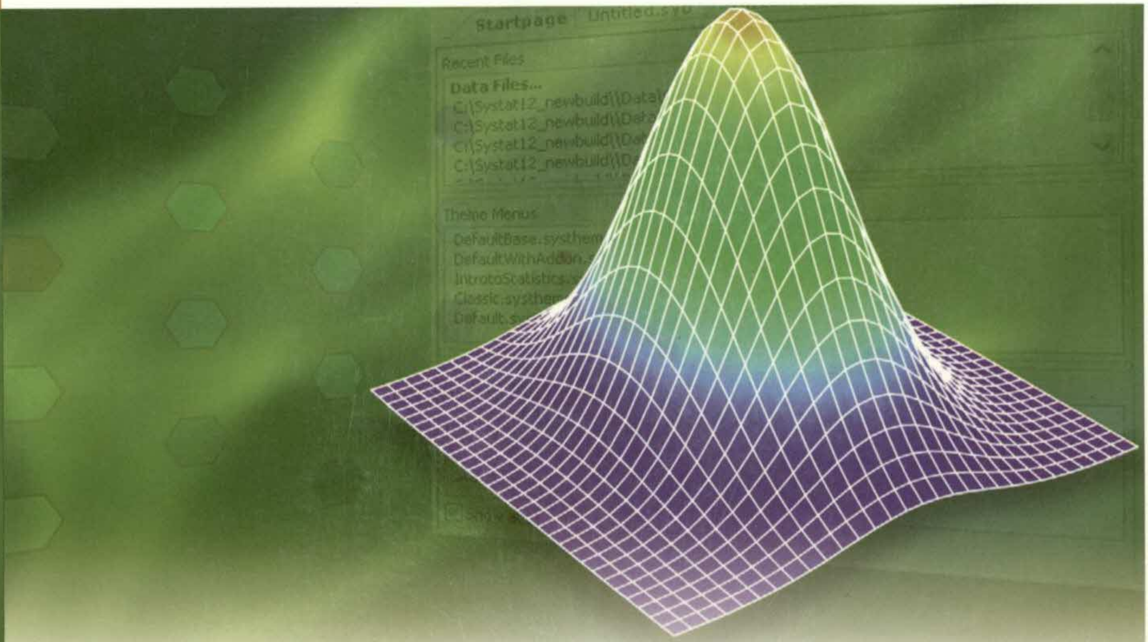
SYSTAT® 12



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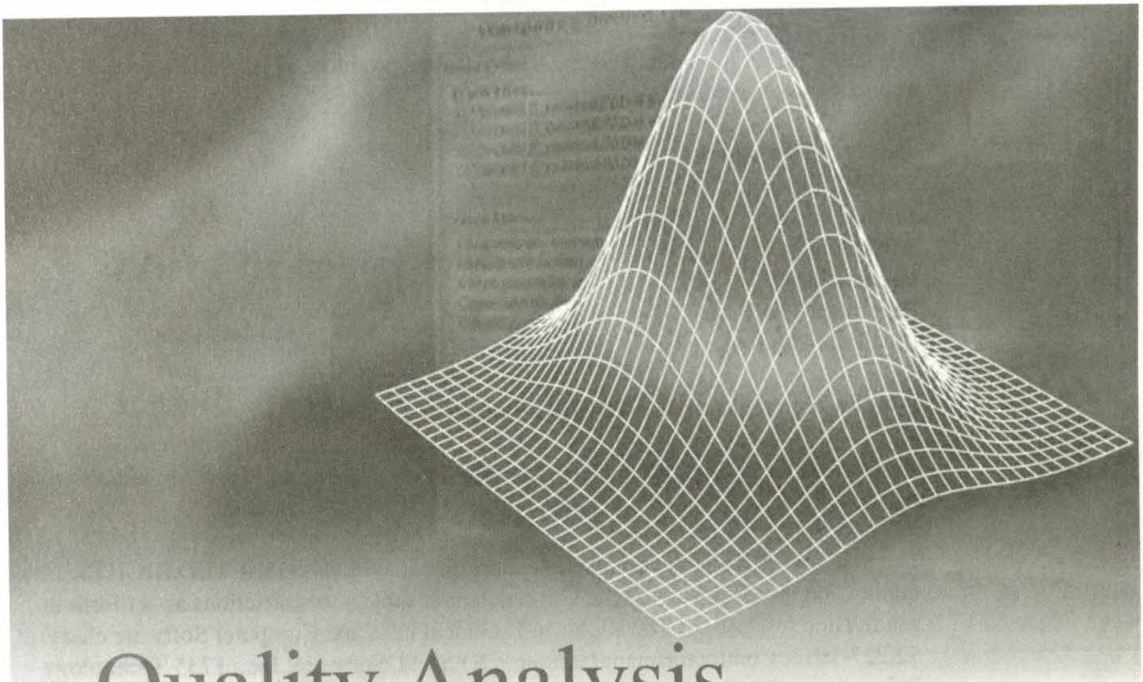

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Quality Analysis

S.K.Adhikari, A.K.Chaudhuri, A.K.Dirghangi, B.K.Manna, and P.R.P.Pillai

The Quality Analysis addon module provides modern quality control and analysis tools like Gauge R & R Studies, Sigma Measurements, Taguchi's Loss Function, and Taguchi's Online Control with the Beta Correction technique. This addon features are the additional tool for quality analysis beyond the traditional quality chart and graphics tools which are available in base SYSTAT.

The first step of many process improvement projects is to conduct a repeatability and reproducibility study. The Gauge Repeatability and Reproducibility (Gauge R & R) Studies feature in SYSTAT provides measures of (a) part-to-part variation, (b) reproducibility, and (c) repeatability in a measurement system, along with suitable graphical display. SYSTAT also provides suitable confidence intervals for the above along with Gauge R & R indices.

Through Sigma Measurements, the sigma level of a process with respect to a quantitative characteristic is calculated for a given DPMO (defects per million opportunity) and vice-versa. Moreover, SYSTAT provides rolled throughput yield for a multiple-step process in this feature.

Depending on the nature of target values, the Taguchi's loss function is computed. Usually, three types of target values are considered: Nominal-the-best, Smaller-the-better, and Larger-the-better. In SYSTAT, all three types are available. Taguchi proposed another measure, namely, signal-to-noise (S/N) ratio to measure the variability around the target value. It is a measure of the reliability of a product, the quality loss function forming the basis for obtaining the S/N ratio. SYSTAT provides S/N ratio for the three types of target values.

Taguchi's Beta Correction technique in SYSTAT determines the magnitude and frequency of process adjustment. It also gives a comparison of quality levels between 'before' and 'after' adjustments using Taguchi's loss function.

Statistical Background

The task of improvement of the quality of a product, process or a service generally follows certain well-defined stages. In the first stage, problems are *define*d; in the second stage, the intensity of the problems is *measure*d; in the third stage, the current state of the process is *analyze*d; in the fourth stage, *improvement* is achieved if there is any scope for it; finally in the fifth stage of *control*, actions are taken to maintain the improved state. To measure the intensity of the problem, gauge R & R studies, and sigma measurements are useful tools. Taguchi's loss function is useful for analyzing the current stage and Taguchi's online control technique can measure the improvement of an ongoing process. The control charts technique can help in monitoring of the process while it is in the control phase.

Gauge R & R Studies

Gauge R & R Studies in SYSTAT provides the capability of a measurement system by determining the total observed variability due to the measuring instrument or gauge. In these studies, two components of measurement systems variability are generated: repeatability and reproducibility. Repeatability represents the variability from the gauge or measurement instrument when it is used to measure the same unit (with the same operator or set-up or in the same time period) repeatedly. Reproducibility reflects the variability arising from different operators, set-ups, or time periods. SYSTAT reports the sources of variability associated with the measurement procedure by using an analysis of variance (ANOVA) approach followed by estimation of the appropriate variance components associated with the sources of variability. A common model used in R & R studies involves two factors: parts and operators.The ANOVA approach enables the estimation of the interaction between parts and operators and also the computation of confidence intervals for the parameters of interest. For an extensive discussion of the ANOVA approach for R & R studies, see Montgomery and Runger (1993-94a, b).

Model

Burdick and Larsen (1997) present methods for constructing confidence intervals for parameters of interest in an R & R study in which the factors considered (part and operator) are random. In particular, they consider the model

$$Y_{ijk} = \mu + P_i + O_j + (PO)_{ij} + R_{ijk}\ ,\ i=1, \ldots, I;\ j=1, \ldots, J;\ k=1, \ldots, K;$$

where μ is a constant, and P_i, O_j, $(PO)_{ij}$, and R_{ijk} are jointly independent normal random variables with means of zero and variance σ^2_P, σ^2_O, σ^2_{PO}, and σ^2_R respectively. These variances are commonly referred to as variance components. The data for an R & R study consist of K repeated measurements of a product characteristic by each of J operators on each of I product samples. There are several variance measures of interest in an R & R study. The variance component σ^2_R measures repeatability. Repeatability is the variation among repeated measurements on a single part made by the same operator. The variance component, σ^2_O, measures variability among operators, and the variance component, σ^2_{PO}, measures the interaction between parts and operators. Montgomery and Runger (1993-94b) define reproducibility, γ_1, as $\sigma^2_O + \sigma^2_{PO}$. Reproducibility describes the variation attributed to different operators measuring the same sample with the same measurement device. The total variability associated with the measurement procedure is the sum of repeatability and reproducibility, namely,

$$\gamma_2 = \sigma^2_O + \sigma^2_{PO} + \sigma^2_R$$

To determine whether a measurement procedure is adequate, the total variability associated with the measurement procedure must be compared with the variability of the process used to produce the parts. A ratio that compares process variability with total variability of the measurement procedure is $\delta = \sigma^2_P/\gamma_2$. This ratio is used to assess the adequacy of a measurement procedure. The *Measurement Systems Analysis Reference Manual* (Automotive Industry Action Group, 1990, p.58) refers to $\sqrt{\delta}$ as the "signal-to-noise ratio".

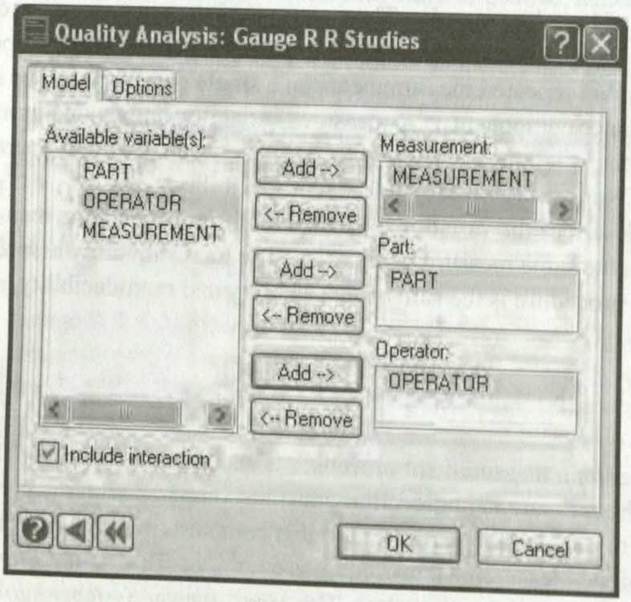
Confidence Intervals on Measures of Variability

Confidence intervals are useful to quantify the uncertainty associated with the results of an R & R study. Several methods have been proposed for constructing confidence intervals of variability in R & R studies. Burdick and Larsen (1997) compared these methods using computer simulation to determine if the intervals maintain the stated level of confidence. They recommend modified large-sample (MLS) intervals for all of the parameters considered in an R & R study. These intervals maintain the stated confidence levels and are comparable in length to alternative methods that maintain the stated confidence level.

Gauge R & R Studies Dialog Box

To open the Gauge R & R Studies dialog box, from the menus choose:

Addons
 Quality Analysis
  Gauge R & R Studies...



Measurement: MEASUREMENT

Part: PART

Operator: OPERATOR

☑ Include interaction

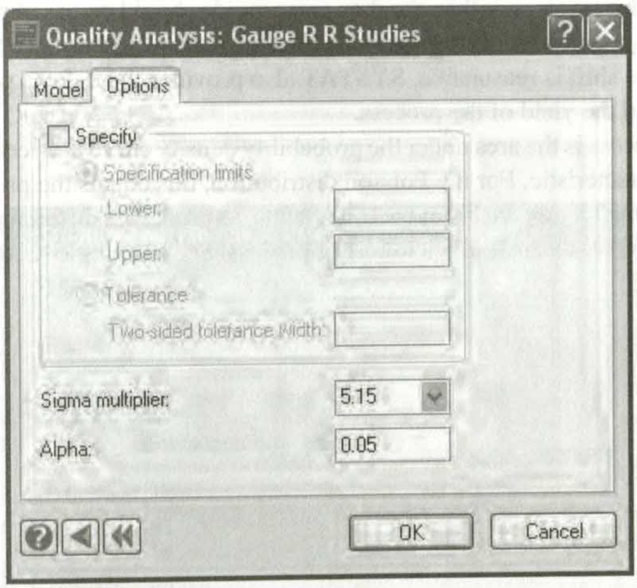
Measurement. Specify the measurement variable. The measurement variable is usually the measurements repeated on each part by the operators. It should be numeric type.

Part. Select a categorical variable that splits your cases into two or more groups as Parts.

Operator. Select a categorical variable that splits your cases into two or more groups as Operators.

Include interaction. You can include interaction between Part effect and Operator effect in your model.

Options



☐ Specify

● Specification limits

Lower:

Upper:

○ Tolerance

Two-sided tolerance width:

Sigma multiplier: 5.15

Alpha: 0.05

Specify. You can specify either Specification limits (Lower and Upper) or Two-sided tolerance width of the measurement.

Sigma multiplier. The multiplier of the standard deviation that defines the percent of the normal distribution that is compared to the tolerance or the process variability. The most common value used is 5.15 since the mean plus or minus (5.15)/2 sigma contains 99.0% of the area under the normal density curve.

Alpha. You can specify the alpha (α) value in (0, 1) to get the $100(1-\alpha)\%$ confidence limits for parameters of interest.

Sigma Measurements

A basic knowledge of sigma measurements (metric) is necessary for any organization to improve its process performance. *Sigma* is a statistical measurement unit that indicates the process efficiency. The idea of sigma measurements comes from the Six-Sigma technique. The sigma measurement unit is directly related to defects per opportunity. The sigma level can be computed by determining the Z values for the defects per unit from the normal distribution table.

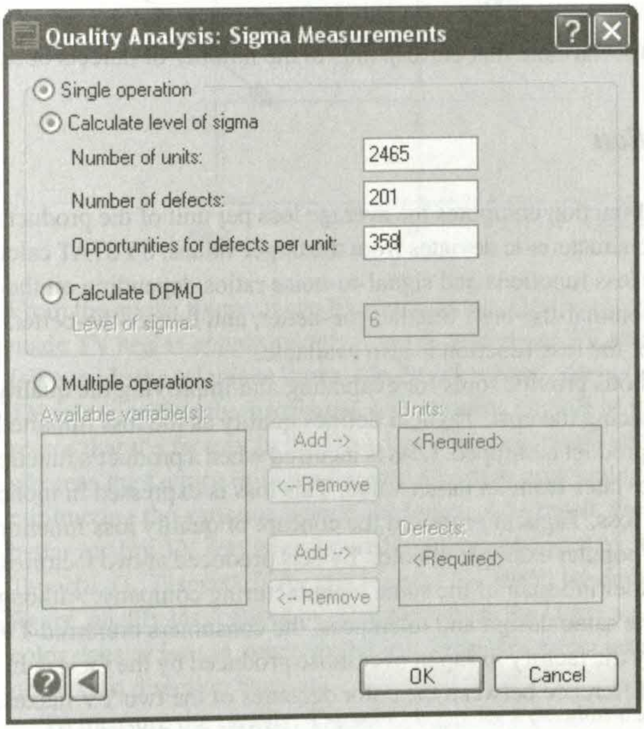
SYSTAT provides sigma levels assuming a possible shift of the center of the process up to ± 1.5 levels. For this, the data you provide should be based on a process running without a shift of its center, or data collected over a long term, where the assumption of no shift is reasonable. SYSTAT also provides the defects per million opportunities and the yield of the process.

Yield of a process is the area under the probability density curve between tolerances of a process characteristic. For the Poisson distribution, this equals the probability of zero failures. Typically the yield for each step within a process is different. The rolled throughput yield gives an overall yield for the process. See Breyfogle (2003) for more details.

Sigma Measurements Dialog Box

To open the Sigma Measurements dialog box, from the menus choose:

Addons
  Quality Analysis
    Sigma Measurements...



Quality Analysis: Sigma Measurements

● Single operation

● Calculate level of sigma

Number of units: 2465

Number of defects: 201

Opportunities for defects per unit: 358

○ Calculate DPMO

Level of sigma: 6

○ Multiple operations

Available variable(s):

Units: <Required>

Defects: <Required>

Single operation. Select this if the number of operation steps involved in the process is one.

Calculate level of sigma. Select this for computing the level of sigma of an ongoing process.

- **Number of units.** Enter the total number of units checked.
- **Number of defects.** Enter the total number of defects observed.
- **Opportunities for defects per unit.** Enter the number of opportunities for a product to be defective.

Calculate DPMO. Select this for computing Defects per Million Opportunities.

- **Level of sigma.** Enter the sigma level of the process.

Multiple operations. In most situations, there may be many steps within a process. SYSTAT computes the rolled throughput yield and normalized yield for such a situation.

Units. Select the variable that corresponds to the number of units checked in different steps.

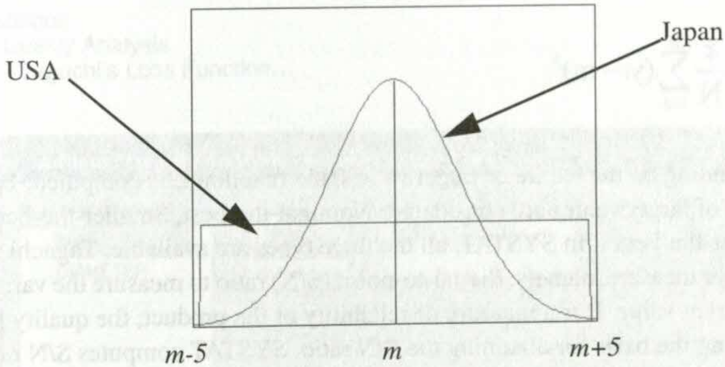
Defects. Select the variable that corresponds to the number of defects observed.

Taguchi's Loss Function

Taguchi's Loss Function computes the average loss per unit of the product that occurs when a quality characteristic deviates from the target values. SYSTAT calculates three types of quality loss functions and signal-to-noise ratios depending on the nature of target values: Nominal-the-best, Smaller-the-better, and Larger-the-better. Graphical representation of the loss function is also available.

Taguchi methods provide tools for evaluating and improving the quality of a product and reducing the cost. Taguchi defines quality as the loss imparted to society from the time a product is shipped. Loss is incurred when a product's functional quality characteristic deviates from its target value. This loss is expressed in monetary units. To measure the loss, Taguchi proposed the concept of quality loss function.

Consider the popular example of color TV sets produced at two factories, one in the USA, and the other in Japan of the same manufacturing company. Although both factories used the same design and tolerances, the consumers preferred TV sets manufactured by the factory in Japan over those produced by the factory in USA. This was due to the difference between the color densities of the two TV makes. The color density distributions are shown below:



From the above figure, it can be seen that the distribution of color density of Japanese-made TV sets is approximately normal, with more TV sets on target and about 0.3% fall outside the tolerance limits. On the other hand, the color density of the USA–made TV sets is uniformly distributed with no units outside of the tolerance limits. Thus it seems that the factory in the USA was only concerned with meeting the tolerances, whereas the factory in Japan focused attention on meeting the target as well as on minimizing the variance around the target. As a result, the factory in Japan produced better quality TV sets as compared to those produced by the factory in USA. See Taguchi, G., Elsayed, E.A., and Hsiang, T. (1989) for details. As shown in the above figure, quality loss caused by deviations from the target value is equal to zero when the color density is at *m*, whereas the loss increases when it moves in either upward or downward direction from *m*.

To measure the quality, Taguchi proposed a quadratic quality loss function as follows:

$$L(y) = k(y - m)^2$$

where

y = quality characteristic value

L(y) = the loss associated with y

k = loss coefficient

m = target (nominal) value.

The loss L(y) represents the cost to society (in monetary units) from the failure of a product to meet its target value for a given quality characteristic. If a large number of parts are considered, say N, the average loss per part is calculated as

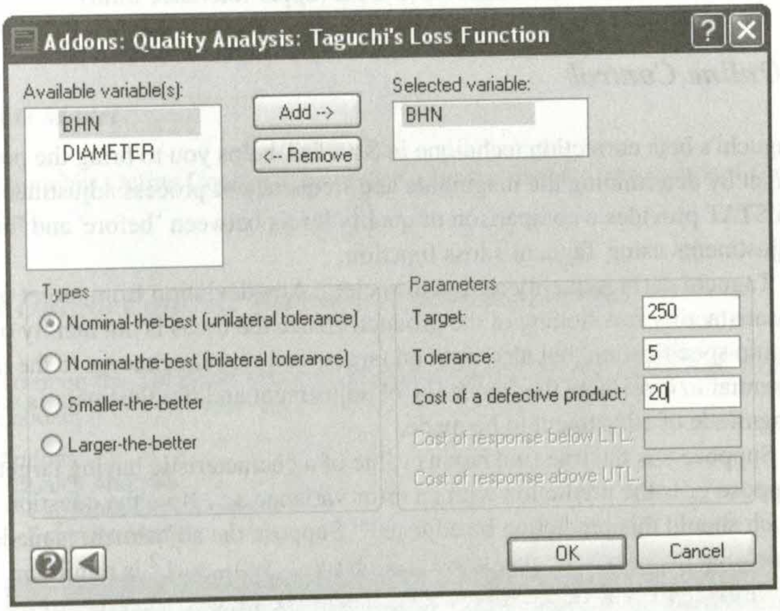
$$L = \frac{k}{N} \sum_{i=1}^{N} (y_i - m)^2$$

Depending on the nature of target values, the function L is computed. Usually, three types of target values are considered: Nominal-the-best, Smaller-the-better, and Larger-the-better. In SYSTAT, all the three types are available. Taguchi proposed another measure, namely, Signal-to-noise (S/N) ratio to measure the variability around the target value. It is a measure of reliability of the product; the quality loss function forming the basis for obtaining the S/N ratio. SYSTAT computes S/N ratio for three types of target values.

Taguchi's Loss Function Dialog Box

To open the Taguchi's Loss Function dialog box, from the menus choose:

Addons
Quality Analysis
Taguchi's Loss Function...



Selected variable: BHN

Types

● Nominal-the-best (unilateral tolerance)

○ Nominal-the-best (bilateral tolerance)

○ Smaller-the-better

○ Larger-the-better

Parameters

Target: 250

Tolerance: 5

Cost of a defective product: 20

Addons: Quality Analysis: Taguchi's Loss Function
Available variable(s):
BHN
DIAMETER
Add -->
<-- Remove
Cost of response below LTL:
Cost of response above UTL:
OK
Cancel

Selected variable. Specify the variable you want to examine. This variable should be continuous and numeric.

Types. Select the type of quality characteristic of the variable:

- Nominal-the-best (unilateral tolerance)
- Nominal-the-best (bilateral tolerance)
- Smaller-the-better
- Larger-the-better

Parameters. This group box depends on the type chosen by the user in the Types group box. These are:

- **Target.** If the type is Nominal-the-best (unilateral or bilateral), you have to input the target value of the measurement.
- **Tolerance.** Enter the tolerance value. For Nominal-the-best: bilateral tolerance you should enter the lower tolerance limit and the upper tolerance limit separately.
- **Cost of a defective product.** Enter the cost of a defective product. For Nominal-the-best: bilateral tolerance, it has to be entered separately for response below LTL (lower tolerance limit) and above UTL (upper tolerance limit).

Taguchi's Online Control

Taguchi's beta correction technique in SYSTAT helps you to bring the process to the target by determining the magnitude and frequency of process adjustment. Besides, SYSTAT provides a comparison of quality levels between `before' and `after' adjustments using Taguchi's loss function.

Taguchi defines quality as loss to society. Any deviation from target results in unsatisfactory functioning of the product. Hence the focus is not merely on producing within specification, but also right on target. To bring the process to the target, it is essential to determine the frequency of adjustment and if adjustment is required, the magnitude of adjustment to be made.

Suppose y is the true (unknown) value of a characteristic having target y_0 and suppose y_p is the prediction with an error variance s_p^2. Now the question is: By how much should this prediction be adjusted? Suppose the adjustment is made with a shrinkage factor b, such that $s^2 = E[y - b(y_p - y_0) - y_0]^2$ is minimum. Then, minimizing the above equation with respect to b, we get

$$\beta = 1 - \frac{1}{F_0}$$

$$\text{where } F_0 = \frac{\sigma_p^2 + \left(y - y_0\right)^2}{\sigma_p^2}$$

Thus the adjustment of y should be as much as $-\beta(y_p - y_0)$.
Note that F_0 is always greater than one and hence $0 \leq \beta \leq 1$. Hence

$$\beta = \begin{cases} 0 & \text{when } F_0 \leq 1 \\ 1-\dfrac{1}{F_0} & \text{when } F_0 > 1 \end{cases}$$

See Taguchi, G., Elsayed, E.A., and Hsiang, T. (1989) for details.

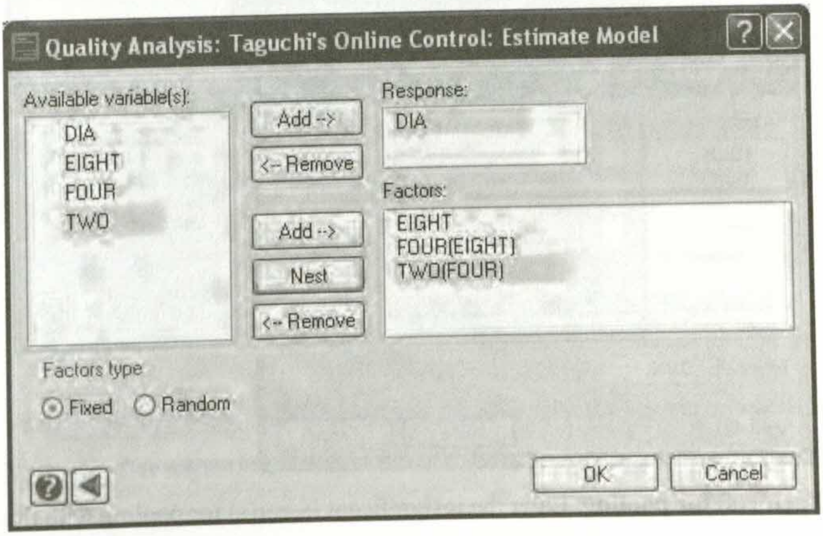
Estimate Model

Taguchi's Online Control is carried out by specifying a nested model and estimating it first.

Taguchi's Online Control: Estimate Model Dialog Box

To open the Taguchi's Online Control: Estimate Model dialog box, from the menus choose:

Addons
 Quality Analysis
  Taguchi's Online Control
  Estimate Model…



Available variable(s):
DIA
EIGHT
FOUR
TWO

Response:
DIA

Factors:
EIGHT
FOUR(EIGHT)
TWO(FOUR)

Factors type
● Fixed ○ Random

Response. Select the variable you want to examine. The response variable should be numeric.

Factors. Select more than one categorical variable. The model you have to build should be of the nested type.

Factors type. You can specify your factors type as either fixed or random by choosing the appropriate button.

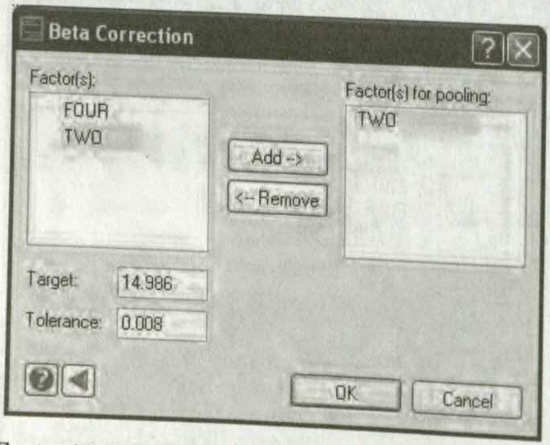
Beta Correction

From the analysis of the model specified, the error variance has to be estimated and then the ready reckoner table used for reading off the magnitude of adjustment required. The user will have the option of getting an estimate of error variance by pooling the insignificant factors. The target and tolerance of the measurement characteristic along with the error variance will provide you the ready reckoner table, a table for the magnitude of adjustment.

Taguchi's Online Control: Beta Correction Dialog Box

To open the Beta Correction dialog box, from the menus choose:

Addons
  Quality Analysis
    Taguchi's Online Control
    Beta Correction...



Factor(s):
FOUR
TWO

Factor(s) for pooling:
TWO

Target: 14.986

Tolerance: 0.008

Factor(s) for pooling. Enter the insignificant factor(s) for pooling with the error term.

Target. Enter the target of the measured quality characteristic.

Tolerance. Enter the tolerance allowed for the measurement.

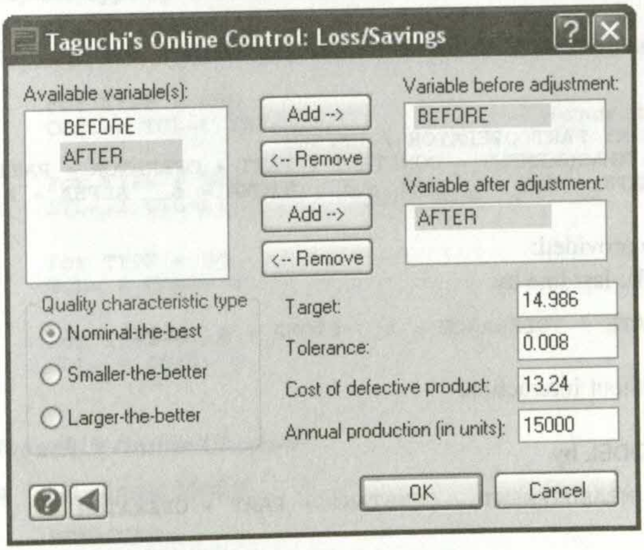
Loss/Savings

This feature will enable comparison of quality levels between before and after adjustment using Taguchi's loss function.

Taguchi's Online Control: Loss/Savings Dialog Box

To open the Loss/Savings Dialog Box, from the menus choose:

Addons
  Quality Analysis
    Taguchi's Online Control
    Loss/Savings…



Variable before adjustment: BEFORE
Variable after adjustment: AFTER
Quality characteristic type
● Nominal-the-best
○ Smaller-the-better
○ Larger-the-better
Target: 14.986
Tolerance: 0.008
Cost of defective product: 13.24
Annual production (in units): 15000

Variable before adjustment. Select the variable with the response before adjustment.

Variable after adjustment. Select the variable with the response after the adjustments are made.

Quality characteristic type. Select the type of quality characteristic of the variable:

- Nominal-the-best
- Smaller-the-better
- Larger-the-better.

Target. Enter the target of the measured quality characteristic.

Tolerance. Enter the tolerance allowed for the measurement.

Cost of defective product. Enter the cost associated with an unacceptable product.

Annual production (in units). Enter the annual production in units.

Using Commands

For Gauge R & R Studies:

- MODEL with Interaction

(a) Specifications about the measurements provided:

```
GAUGE
  USE filename
  CATEGORY PART OPERATOR / EFFECT
  MODEL MEASUREMENT = CONSTANT + PART + OPERATOR + PART*OPERATOR
  ESTIMATE / USL = u  LSL = l   SIGMA = s   ALPHA = a
```

(b) Tolerance provided:
Replace the last line by

```
ESTIMATE / TOLERANCE = t   SIGMA = s  ALPHA = a
```

- MODEL without Interaction.

Replace MODEL by

```
MODEL MEASUREMENT = CONSTANT + PART + OPERATOR
```

For Sigma Measurements:

- To find the level of sigma:

```
MSIGMA
  MEASURE/ UNIT= u  DEFECT= d   OPPORTUNITY =o
```

- To find DPMO:

```
MSIGMA
  MEASURE/ SIGMA=s
```

Note that Single Operation option does not require data files.

- For Multiple Operations:

```
MSIGMA
  USE filename
  MEASURE/ UNIT= Var1  DEFECT= Var2
```

For Taguchi's Loss Function:

```
TLOSS
  USE filename
  LOSS varname
  ESTIMATE/ TYPE=type PARAMETER
```

Replace *`type`* by NBU, NBB, SB or LB.

Replace `PARAMETER` by the following based on the chosen type:

```
For TYPE = NBU
COST=c TOL=t TAR=m

For TYPE = NBB
LTL=l1 UTL=u1 CRB=c1 CRA=c2 TAR= m

For TYPE = SB
TOL= t COST= c

For TYPE = LB
TOL= m COST= c
```

For Taguchi's Online Control:

- To Estimate Model:

```
BETACORR
  USE filename
  CATEGORY
  MODEL Var = CONSTANT + Var1 + Var2(Var1) +… / RANDOM, FIXED
  ESTIMATE
```

- For Beta correction:

```
POOL Varname
ESTIMATE / TAR=m  TOL=t
```

- For Loss/Savings:

```
SAVING
   BEFORE Var1
   AFTER Var2
   ESTIMATE/ Type =type   PROD = p   PARAMETER
```

Replace `type` by NB, SB or LB.

Replace `PARAMETER` by the following based on the chosen type:

```
For TYPE = NB
COST=c TOL=t   TAR=m

For TYPE = SB
TOL= t  COST= c

For TYPE = LB
TOL= t  COST= c
```

Usage Considerations

Types of data. Rectangular data file is used for GAUGE, BETACORR, and TLOSS. GAUGE and BETACORR also require balanced data. For MSIGMA a rectangular data file is used, if required.

Print options. The output is standard for all PLENGTH options.

Quick Graphs. GAUGE produces graphs of average measurement at different parts, operators and interaction between parts and operators. In MSIGMA, the graph displays the yield density and throughput yield operation-wise. SYSTAT produces Taguchi's Loss Function of the selected quality characteristic. In BETACORR, SYSTAT plots the line graph of measurements for before and after adjustments if user wants to compute loss/savings.

Saving files. Saving option is not available in any of the modules.

BY groups. GAUGE, MSIGMA and TLOSS perform separate analyses for each level of any BY variables.

Case frequencies. TLOSS uses a frequency variable, if present, to duplicate cases.

Case weights. Case weighting is not available in any of the modules.

Examples

Example 1
Gauge R & R Studies With Interaction

The goal of the Gauge R&R studies is to determine whether the measurement procedure is adequate for monitoring the process. For that the total variability (sum of repeatability and reproducibility) associated with the measurement procedure has to be compared with the variability of the process used to produce this item.

In this example we examine the measurements made by three operators (*PERSON*) on ten parts (*ITEM*) of a product. The data in the *GAUGE1* are from Smith (2001). Each item is measured three times by each person. We start with the full model by considering interaction between *ITEM* and *PERSON*.

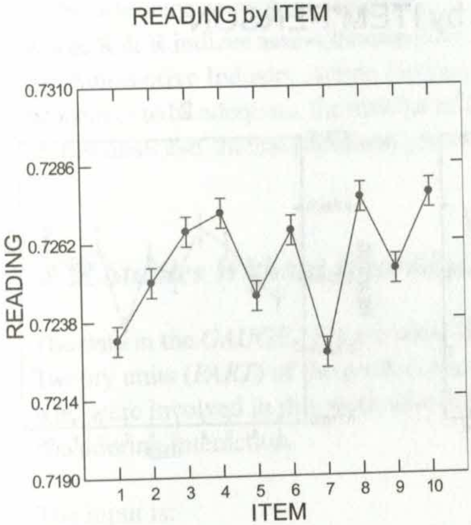
Under the default case, the input is:

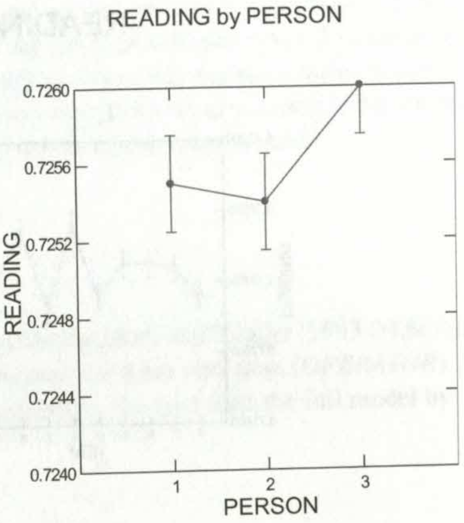
```
GAUGE
  USE GAUGE1
  CATEGORY ITEM PERSON / EFFECT
  MODEL READING = CONSTANT + ITEM + PERSON + ITEM * PERSON
  ESTIMATE
```

The output is:

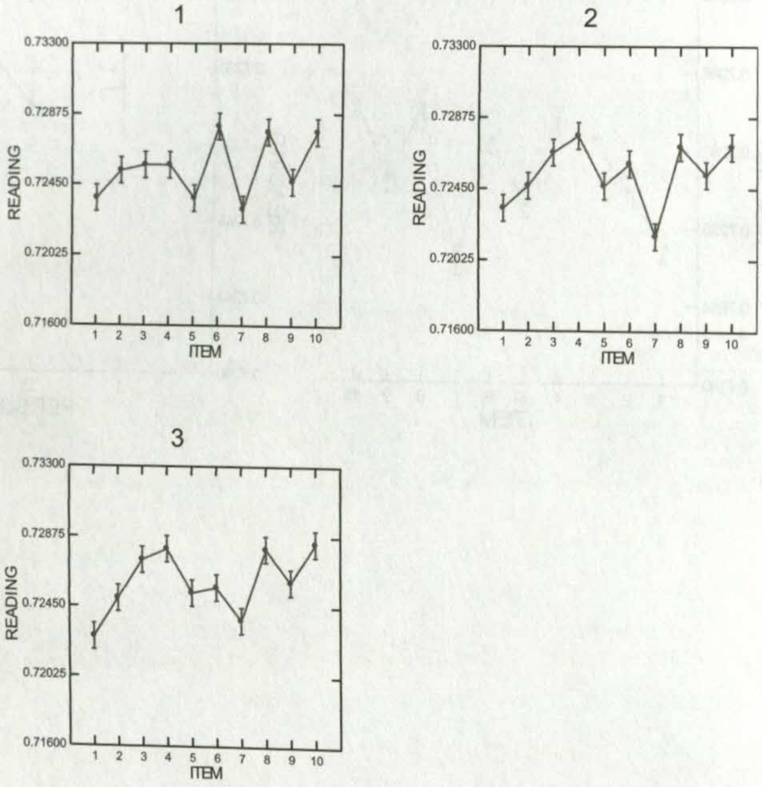
```
Gauge R & R Studies

R&R Studies

ITEM          ¦ 10
--------------+---
PERSON        ¦  3
REPLICATION   ¦  3

Measurement Variable : READING
N                    : 90

Analysis of Variance
Source       ¦          SS   df   Mean Squares        F-ratio      p-value
-------------+-------------------------------------------------------------
ITEM         ¦ 0.00024601     9     0.00002733    13.41066021   0.00000274
PERSON       ¦ 0.00000620     2     0.00000310     1.52089643   0.24530583
ITEM*PERSON  ¦ 0.00003669    18     0.00000204     1.07277453   0.40008674
Error        ¦ 0.00011400    60     0.00000190
```

```
Measurement Analysis Report

Variance
                      |                    % Total
Terms                 |     Variance      Variance     95% Confidence Interval
                      |                                   Lower         Upper
----------------------+------------------------------------------------------
ITEM                  | 0.00000281     58.65178188    0.00000119    0.00000989
PERSON                | 0.00000004                    0.00000000    0.00000401
ITEM*PERSON           | 0.00000005                    0.00000000    0.00000086
Repeatability         | 0.00000190     39.64791756    0.00000137    0.00000282
Reproducibility       | 0.00000008      1.70030056    0.00000000    0.00000411
Measurement Error     | 0.00000198     41.34821812    0.00000153    0.00000607
Total                 | 0.00000479


Process Variation
                      |  Standard    5.15x Standard    % Total
Terms                 |  Deviation      Deviation     Variation    95% Confidence Interval
                      |                                               Lower       Upper
----------------------+------------------------------------------------------------------
ITEM                  | 0.001676       0.008634      76.584451    0.005625    0.016194
PERSON                | 0.000188       0.000968       8.593685    0.000000    0.010309
ITEM*PERSON           | 0.000214       0.001105       9.807069    0.000000    0.004782
Repeatability         | 0.001378       0.007098      62.966592    0.006024    0.008642
Reproducibility       | 0.000285       0.001470      13.039557    0.000000    0.010445
Measurement Error     | 0.001407       0.007249      64.302580    0.006379    0.012689
Total                 | 0.002189       0.011273


Gauge R&R Indices

Index                   |    Value
------------------------+------------
Distinct Categories     | 1.68433008
Signal-to-Noise Ratio   | 1.19100122
Precision-to-Tolerance  |
```





1.06.2010
14004



READING by ITEM*PERSON

The Gauge R & R Studies begin with the Analysis of Variance table which shows *ITEM* is a significant effect (p<0.0005), but *PERSON* (p=0.245306) and *ITEM*PERSON* (p=0.400087) are not significant.

The measurement analysis report decomposes the overall variation into variability associated with the measurement procedure and variability associated with the process to produce the items. Note that the percentage of total variance of measurement error is 41.3, which is far too high and hence the measurement systems need to be improved. The 95% confidence intervals on the parameters (you can get it by specifying ALPHA) quantify the uncertainty associated with this study.

The 5.15 times standard deviation covers 99% of the normal distribution compared to the tolerance or process variability. You can specify SIGMA of your choice. The gauge R & R indices assess the adequacy of the measurement procedure. For instance, the Automotive Industry Action Group (1990) recommends that for a measurement procedure to be adequate, the number of distinct categories should exceed 3; this shows that in this case, the measurement procedure needs further improvement.

Example 2
Gauge R & R Studies Without Interaction

The data in the *GAUGE2* file are taken from Montgomery and Runger (1993-94,6(1)). Twenty units (*PART*) of the product are obtained and three operators (*OPERATOR*) who were involved in this work take measurements. We start with the full model by considering interaction.

The input is:

```
GAUGE
    USE GAUGE2
    CATEGORY PART OPERATOR / EFFECT
    MODEL MEASUREMENT = CONSTANT + PART + OPERATOR + PART*OPERATOR
    ESTIMATE
```

The output is:

```
Gauge R & R Studies


R&R Studies

PART        | 20
------------+---
OPERATOR    |  3
REPLICATION |  2

Measurement Variable : MEASUREMENT
N                    : 120
```

```
Analysis of Variance

Source        |          SS   df   Mean Squares     F-ratio     p-value
--------------+--------------------------------------------------------
PART          | 1185.425000   19      62.390789   87.646950    0.000000
OPERATOR      |    2.616667    2       1.308333    1.837954    0.173010
PART*OPERATOR |   27.050000   38       0.711842    0.717824    0.861434
Error         |   59.500000   60       0.991667

*** WARNING *** : Some of the variance components are negative.
Try  MODEL without interaction.
```

Now let us consider the reduced model by omitting the interaction between *PART* and *OPERATOR*. Further the tolerance (difference between upper and lower specifications) of the measurement was 10.

The input is:

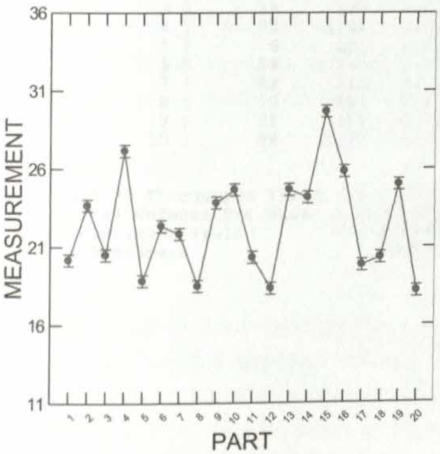
```
MODEL MEASUREMENT = CONSTANT + PART + OPERATOR
ESTIMATE/TOL=10
```

The output is:

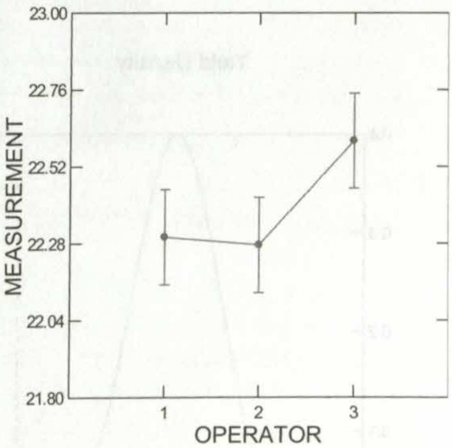
```
Gauge R & R Studies


R&R Studies


PART         | 20
-------------+---
OPERATOR     |  3
REPLICATION  |  2

Measurement Variable : MEASUREMENT
N                    : 120

Analysis of Variance

Source   |          SS   df   Mean Squares     F-ratio     p-value
---------+--------------------------------------------------------
PART     | 1185.425000   19      62.390789   70.644684    0.000000
OPERATOR |    2.616667    2       1.308333    1.481417    0.232361
Error    |   86.550000   98       0.883163

Measurement Analysis Report

Variance

                  |                % Total
Terms             |   Variance     Variance   95% Confidence Interval
                  |                                Lower        Upper
------------------+--------------------------------------------------
PART              |  10.251271    91.980373     5.865226    22.033817
OPERATOR          |   0.010629                  0.000000     1.269236
Repeatability     |   0.883163     7.924255     0.679986     1.193778
Reproducibility   |   0.010629                  0.000000     1.269236
```

```
Measurement Error |  0.893793    8.019627       0.000000       9.084774
Total             | 11.145064

Process Variation

                  | Standard  5.15x Standard    % Total
Terms             | Deviation      Deviation  Variation   95% Confidence Interval
                  |                                           Lower           Upper
------------------+-----------------------------------------------------------------
PART              | 3.201761      16.489067  95.906399    12.472388       24.174199
OPERATOR          | 0.103098       0.530956   3.088233     0.000000        5.802010
Repeatability     | 0.939768       4.839803  28.150053     4.246754        5.626897
Reproducibility   | 0.103098       0.530956   3.088233     0.000000        5.802010
Measurement Error | 0.945406       4.868841  28.318946     0.000000       15.522594
Total             | 3.338422      17.192875

Gauge R&R Indices

Index                  |     Value
-----------------------+-----------
Distinct Categories    |  4.789448
Signal-to-Noise Ratio  |  3.386651
Precision-to-Tolerance | 56.724360
```

MEASUREMENT by PART



MEASUREMENT by OPERATOR



The part-to-part variation is significant ($p < 0.0005$). The measurement analysis report shows that the percentage of total variance of measurement error (just 8%) is negligible compared to the part-to-part variation. The indices also show that measurement error can be ignored in decision-making.

Example 3
DPMO and Level of Sigma of a Process

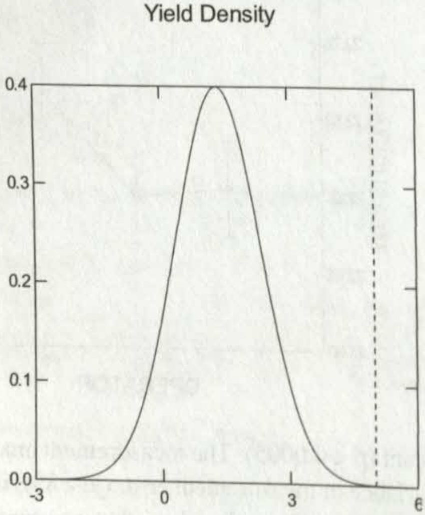
A study was conducted on the defects produced by a printed circuit board factory. It was found that over a period of time, out of 2465 items produced, 201 were defective. The number of opportunities of a product to be defective was approximately 358. The QC engineer is interested to know under what sigma level the process is running.

The input is:

```
MSIGMA
   MEASURE / UNIT = 2465 DEFECT = 201 OPPORTUNITY = 358
```

The output is:

```
Sigma Measurements


Defects Per Million Opportunities : 227.769783
Level of Sigma                    :   5.005623
Process Yield(%)                  :  99.977223
```



The output gives the short-term sigma level by assuming that you provided long-term data.

Example 4
Rolled Throughput Yield in Multiple Operations

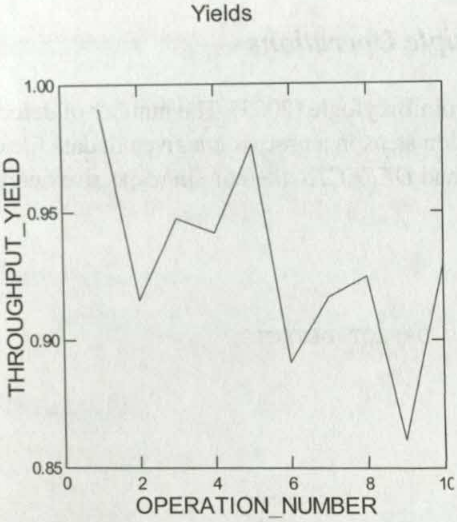
We use a data set *PROCESS* from Breyfogle (2003). The number of defects and units produced over different operation steps in a process are given in data file containing data on the number of *UNITS* and *DEFECTS* thereof in respective operations.

The input is:

```
MSIGMA
   USE PROCESS
   MEASURE/UNIT=UNITS DEFECT=DEFECTS
```

The output is:

```
Sigma Measurements

          |                                  Throughput
Operation | Defects   Units        DPU          yield
----------+--------------------------------------------
        1 |       5     523   0.009560       0.990485
        2 |      75     851   0.088132       0.915640
        3 |      18     334   0.053892       0.947534
        4 |      72    1202   0.059900       0.941859
        5 |       6     252   0.023810       0.976472
        6 |      28     243   0.115226       0.891164
        7 |      82     943   0.086957       0.916717
        8 |      70     894   0.078300       0.924687
        9 |      35     234   0.149573       0.861076
       10 |      88    1200   0.073333       0.929291

 Rolled Throughput Yield : 0.477743
 Total Defects Per Unit  : 0.738682
 Normalized Yield        : 0.928794
 Z Benchmark             : 2.966868
```



The rolled throughput yield gives the overall yield of the process. This is important because yield for each operation in a process may differ. Z benchmark helps the organization as the best direct competitor. Organizations are considered world class if they are at the 6σ level in the "short-term" or 4.5σ in the "long-term".

Example 5
Taguchi Loss for Nominal-the-Best Quality Characteristic with Unequal Tolerances

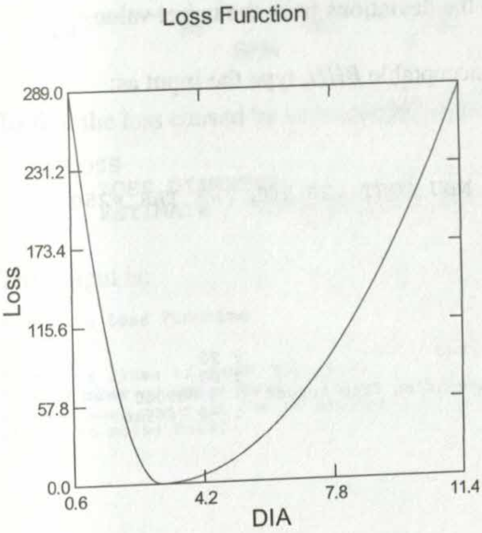
The most general case of the bilateral tolerance system is where the tolerance limits are set at unequal distances from the target value. This example is from Taguchi, Elsayed, and Hsiang (1989), where we examine the quality levels during a two-month production time of the clearance between the cylinder and piston of a six-cylinder engine. The manufacturer requires that this clearance should be 3^{-2}_{+7} mm. Defect loss for each cylinder and piston assembly is $200.

The input is:

```
TLOSS
    USE PISTON
    BY MONTHS
    LOSS DIA
    ESTIMATE / TYPE=NBB TAR=3 LTL=2 UTL=7 CRB=200 CRA=200
```

The output is:

```
Results for MONTHS = 1.000000
Number of lines of input data read                   : 23
Total number of Cases Used                           : 23
Average Loss per part due to deviation from target: 87.488909
Signal to noice Ratio                                : -8.886922
```



```
Results for MONTHS = 2.000000

Number of lines of input data read                   : 20
Total number of Cases Used                           : 20
Average Loss per part due to deviation from target: 58.724490
Signal to noice Ratio                                : -7.745170
```

So the quality level of the second month is better than that of the first month by an amount of = \$ 87.488909 - \$ 58.724490= \$ 28.764419 per unit.

If we consider the Signal-to-noise ratio here, we arrive at the same conclusion, that is, since the second month has a higher S/N Ratio value, it is a better month than the first.

Example 6
Taguchi Loss for Nominal-the-Best Quality Characteristic with Equal Tolerances

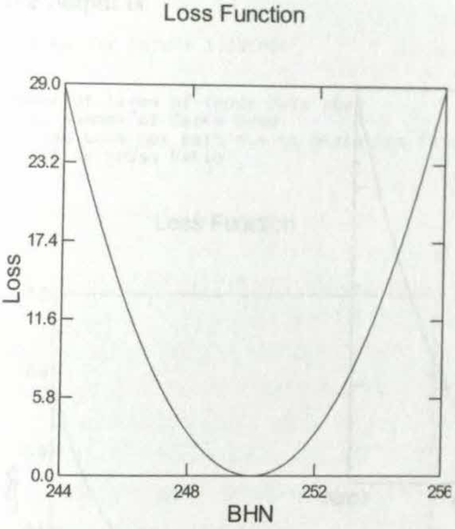
This data set *HARDDIA* is also from Taguchi, Elsayed, and Hsiang (1989). Two characteristics of a product---hardness (given by the corresponding *BHN*) and circular diameter (*DIAMETER*)---were measured for 20 samples. Specifications for hardness and diameter are 250 ± 5 and 1.0000 ± 0.002 respectively. The loss of a defective product for hardness is $20 and for diameter is $30. We are interested in calculating the total expected loss caused by the deviations from the target value.

To find the loss caused by unacceptable *BHN*, type the input as:

```
TLOSS
   USE HARDDIA
   LOSS BHN
   ESTIMATE / TYPE= NBU COST =20 TOL  =5 TAR =250
```

The output is:

```
Taguchi's Loss Function

Number of lines of input data read                    : 20
Total number of Cases Used                            : 20
Average Loss per part due to deviation from target    : 3.800000
Signal to noise Ratio                                 : -6.766936
```

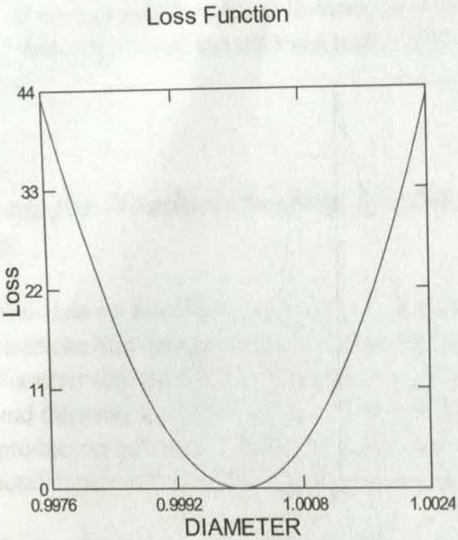


To find the loss caused by unacceptable diameter size, the input is:

```
TLOSS
   LOSS DIAMETER
   ESTIMATE / TYPE= NBU COST =30 TOL  =0.002 TAR =1.0000
```

The output is:

```
Taguchi's Loss Function


Number of lines of input data read                       : 20
Total number of Cases Used                               : 20
Average Loss per part due to deviation from target      : 10.541250
Signal to noise Ratio                                    : 58.521692
```



Thus the total expected loss caused by the deviations from target values is = \$3.80000 + \$10.54125 = \$14.34125.

Example 7
Taguchi Loss for Larger-the-Better Quality Characteristic

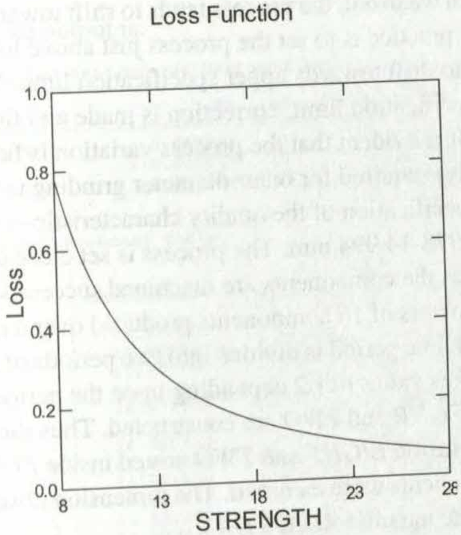
There are characteristics for which larger-the-better is applicable; examples are: tensile strength of materials and fuel efficiency. In such cases, there are no predetermined target values, and the larger the value of the characteristic, the better it is. See Taguchi, Elsayed, and Hsiang (1989) for further details. We consider tensile strength data in kg/mm from the data file *THREAD* where thread samples are collected every day in a month's production for two consecutive months. The defect loss is \$0.5 per linear meter and the lower specification limit is 10 kg/mm2.

The input is:

```
TLOSS
   USE THREAD
   BY MONTH
   LOSS STRENGTH
   ESTIMATE /TYPE=LB TOL=10 COST=0.5
```

The output is:

```
Results for ONTH = 1.000000


Number of lines of input data read                     : 23
Total number of Cases Used                             : 23
Average Loss per part due to deviation from target     : 0.284082
Signal to noise Ratio                                  : 22.455266
```



```
Results for MONTH = 2.000000


Number of lines of input data read                     : 20
Total number of Cases Used                             : 20
Average Loss per part due to deviation from target     : 0.293418
Signal to noise Ratio                                  : 22.314833
```

So the quality level of the first month is better than that of the second one by an amount of = \$ 0.293418 - \$ 0.284082 = \$ 0.009336. The same conclusion is obtained by considering the S/N ratio.

Example 8
Taguchi's Beta Correction Adjustment

A grinding machine used extensively for outer diameter grinding was suffering from tool wear. A number of components are produced from the machine of which one component was considered for the study.

On account of the gradual tool wear-out, the process tends to shift towards the upper specification limit. The general practice is to set the process just above lower specification limit and allow it to drift towards upper specification limit. When the process is close to the upper specification limit, correction is made and the process is brought to the original setting. It is evident that the process variation is far too large.

The component (adaptor body) required for outer diameter grinding is being considered for the study. The specification of the quality characteristic--- outer diameter after grinding--- is 14.978-14.994 mm. The process is set close to its target and the outer diameter is noted as the components are machined successively.

The data set contains the diameters of 16 components produced over a period of 16 hours one in each hour. The total time period is divided into two periods of eight hours each and the variable *EIGHT* takes value 1 or 2 depending upon the period of its production. Similarly variables *FOUR* and *TWO* are constructed. Thus the 'design' is a nested one with *FOUR* nested inside *EIGHT* and *TWO* nested inside *FOUR*.

The data for the first 16 components were recorded. The dimension observed in the order of production is given in the data file *ADAPTOR*

To estimate the model, the input is:

```
BETACORR
    USE ADAPTOR
    CATEGORY EIGHT FOUR TWO
    MODEL DIA=CONSTANT+EIGHT+FOUR(EIGHT)+TWO(FOUR)
    ESTIMATE
```

The output is:

```
Taguchi's Beta Correction

Analysis of Variance Table when Factors are Fixed

Source       ¦        SS   df   Mean Squares       F-ratio     p-value
-------------+---------------------------------------------------------
EIGHT        ¦ 0.000033     1       0.000033    176.333333    0.000001
FOUR(EIGHT)  ¦ 0.000011     2       0.000005     28.333333    0.000234
TWO(FOUR)    ¦ 0.000002     4       0.000001      3.000000    0.087040
Error        ¦ 0.000002     8       0.000000
```

The *p*-value for TWO (FOUR) shows insignificance of that factor. Hence for pooling the insignificant factor with error, use POOL and for the ready reckoner table, input TARGET, and TOLERANCE through the following commands. The continued input is:

```
POOL TWO
ESTIMATE/TARGET=14.986 TOLERANCE=0.008
```

The output is:

```
Pooled Analysis of Variance Table when Factors are Fixed

            |       SS   df   Mean Squares      F-ratio     p-value
------------+-------------------------------------------------------
EIGHT       | 0.000033    1       0.000033   105.800000    0.000000
            | 0.000011    2       0.000005    17.000000    0.000315
Error       | 0.000004   12       0.000000

Ready Reckoner Table:

     |                                                         Extent of
     | Measurement   Deviation       F-ratio       Beta     Adjustment
-----+-----------------------------------------------------------------
   1 |   14.976400   -0.009600    294.912000   0.996609       0.009567
   2 |   14.977040   -0.008960    256.901120   0.996107       0.008925
   3 |   14.977680   -0.008320    221.511680   0.995486       0.008282
   4 |   14.978320   -0.007680    188.743680   0.994702       0.007639
   5 |   14.978960   -0.007040    158.597120   0.993695       0.006996
   6 |   14.979600   -0.006400    131.072000   0.992371       0.006351
   7 |   14.980240   -0.005760    106.168320   0.990581       0.005706
   8 |   14.980880   -0.005120     83.886080   0.988079       0.005059
   9 |   14.981520   -0.004480     64.225280   0.984430       0.004410
  10 |   14.982160   -0.003840     47.185920   0.978807       0.003759
  11 |   14.982800   -0.003200     32.768000   0.969482       0.003102
  12 |   14.983440   -0.002560     20.971520   0.952316       0.002438
  13 |   14.984080   -0.001920     11.796480   0.915229       0.001757
  14 |   14.984720   -0.001280      5.242880   0.809265       0.001036
  15 |   14.985360   -0.000640      1.310720   0.237061       0.000152
  16 |   14.986000    0.000000      0.000000   0.000000       0.000000
  17 |   14.986640    0.000640      1.310720   0.237061      -0.000152
  18 |   14.987280    0.001280      5.242880   0.809265      -0.001036
  19 |   14.987920    0.001920     11.796480   0.915229      -0.001757
  20 |   14.988560    0.002560     20.971520   0.952316      -0.002438
  21 |   14.989200    0.003200     32.768000   0.969482      -0.003102
  22 |   14.989840    0.003840     47.185920   0.978807      -0.003759
  23 |   14.990480    0.004480     64.225280   0.984430      -0.004410
  24 |   14.991120    0.005120     83.886080   0.988079      -0.005059
  25 |   14.991760    0.005760    106.168320   0.990581      -0.005706
  26 |   14.992400    0.006400    131.072000   0.992371      -0.006351
  27 |   14.993040    0.007040    158.597120   0.993695      -0.006996
  28 |   14.993680    0.007680    188.743680   0.994702      -0.007639
  29 |   14.994320    0.008320    221.511680   0.995486      -0.008282
  30 |   14.994960    0.008960    256.901120   0.996107      -0.008925
  31 |   14.995600    0.009600    294.912000   0.996609      -0.009567
```

The ready reckoner table with the first and last columns was given to the operator. 46 components were machined and adjustments were given as per the ready reckoner. The dimensions recorded sequentially are given in the data file *ADJADAPTOR*. The savings after the adjustments can be computed by giving the following input:

```
SAVING
   USE ADJADAPTOR
   BEFORE BEFORE
   AFTER AFTER
   ESTIMATE/ TYPE=NB  TAR=14.986  TOL=0.008  COST=13.24
            PROD=15000
```

The output is:

```
Loss/Savings


Savings:
Loss per unit before implementation = 0.96972656
Loss per unit after implementation  = 0.32830163
Savings per unit                    = 0.64142493
Annual production                   = 1.50000000E+003
Annual savings                      = 962.13739810
Capability Comparison:
The capability of the process before implementation =  1.23168057
The capability of the process after  implementation =  2.11683115
```

Chart: Before implementing Beta correction

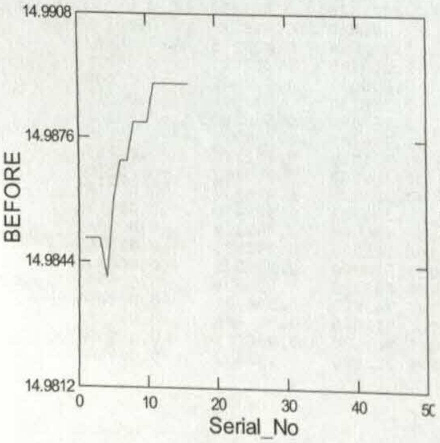
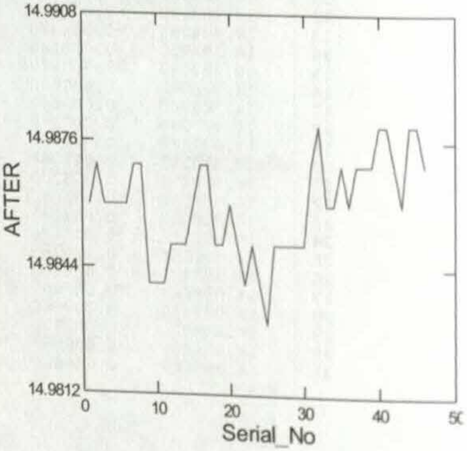


Chart: After implementing Beta correction



The application of beta correction has improved the performance of the process tremendously as is evident from the run charts shown above. The savings are small, but significant for one component. The outcome of this study has stimulated an urge to reduce the high variation observed in such tool-wear associated processes.

References

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Burdick, R.K. and Larsen G.A (1997). Confidence interval on measures of variability in R & R studies. *Journal of Quality Technology,* 29, 261-273.

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Montgomery, D.C. and Runger, G.C. (1993-94a). Gauge capability and designed experiments Part 1, Experimental design models and variance component estimation. *Quality Engineering,* 6(1), 115-135.

Montgomery, D.C and Runger, G.C. (1993-94b). Gauge capability and designed experiments Part 2, Experimental design models and variance component estimation. *Quality Engineering,* 6(2), 289-305.

Smith, G.M (2001).*Statistical process control and quality improvement*, 4th ed. Englewood Cliffs, NJ: Prentice Hall.

Taguchi, G., Elsayed, E.A., and Hsiang, T. (1989). *Quality engineering in production systems*. New York: McGraw–Hill.

(*indicates additional references)

The ready reckoner table with the first and last columns was given to the operator. 46 components were machined and adjustments were given as per the ready reckoner. The dimensions recorded sequentially are given in the data file *ADJADAPTOR*. The savings after the adjustments can be computed by giving the following input:

```
SAVING
   USE ADJADAPTOR
   BEFORE BEFORE
   AFTER AFTER
   ESTIMATE/ TYPE=NB  TAR=14.986  TOL=0.008  COST=13.24
            PROD=15000
```

The output is:

```
Loss/Savings


Savings:
Loss per unit before implementation = 0.96972656
Loss per unit after implementation  = 0.32830163
Savings per unit                    = 0.64142493
Annual production                   = 1.50000000E+003
Annual savings                      = 962.13739810
Capability Comparison:
The capability of the process before implementation =  1.23168057
The capability of the process after  implementation =  2.11683115
```

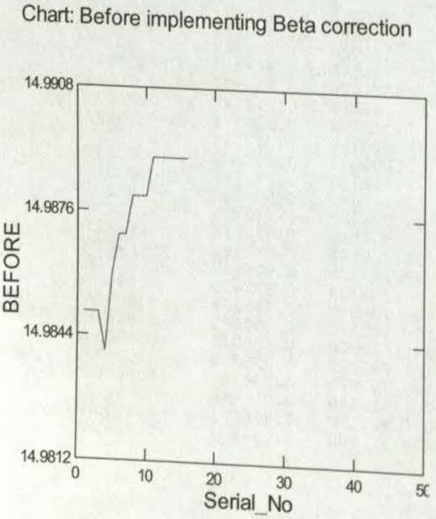
Chart: Before implementing Beta correction

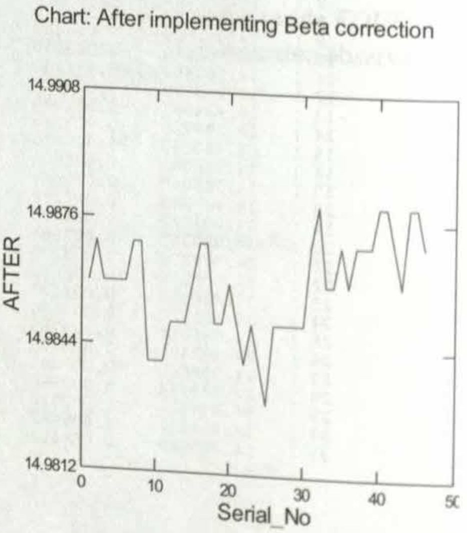
Chart: After implementing Beta correction

The application of beta correction has improved the performance of the process tremendously as is evident from the run charts shown above. The savings are small, but significant for one component. The outcome of this study has stimulated an urge to reduce the high variation observed in such tool-wear associated processes.

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(*indicates additional references)

Language Reference-Quality Analysis

BETACORR:Taguchi's on-line control: Beta Correction Technique

BETACORR brings a process to target by determining the magnitude and frequency of process adjustment. Further, it gives a comparison of quality levels before and after adjustments using Taguchi's Loss function.

Setup:

```
      * BETACORR
      *    USE
      *    MODEL
           CATEGORY
      *    POOL
HOT   *    ESTIMATE
```

Model Building

MODEL command

MODEL *var* = CONSTANT + *var1* + *var2 (var1)* +...

Specifies the linear model to estimate. The parentheses denote nested factors.

/ FIXED	all factors considered are assumed to be fixed.
RAND	all factors considered are assumed to be random.

CATEGORY command

```
CATEGORY grpvarlist
```

Specifies numeric or string grouping variables to define cells.

POOL command

```
POOL varlist
```

Pool the insignificant factors. Since BETACORR estimates a nested model, POOL allows pooling of insignificant factors from the lower order of nesting.

ESTIMATE command

```
ESTIMATE
```

Tells SYSTAT to estimate the model and re-estimate after pooling the insignificant factors.

/ TARGET=*n*	target value of the response.
TOLERANCE=*n*	tolerance allowed in the response.

GAUGE:Gauge R & R Studies

GAUGE provides the capability of a measurement system by determining the total observed variability due to the measuring instrument or gauge. The methodology is based on two-way analysis of variance for random effect model with or without interaction. Part and operator are considered here as two factors for a measurement data.

Setup:

```
      * GAUGE
      *    USE
           CATEGORY
      *    MODEL
HOT   *    ESTIMATE
```

CATEGORY command

CATEGORY *grpvarname*

Specifies part and operator grouping variables that define cells.

MODEL command

MODEL *var1* = CONSTANT + *var2* + *var3* + *var2** *var3*

Specifies the model to estimate. *var1* specifies the measurement variable, *var2* and *var3* respectively specify the part and operator variables. Specify interaction by linking *var2* and *var3* with an asterisk. Interaction term in a model is optional.

ESTIMATE Command

ESTIMATE

Causes the previously specified model to be estimate.

/ TOLERANCE = *n*	specifies two sided tolerance value of product parameter for this measurement.
USL = *n* LSL = *n*	instead of specifying tolerance, product upper specification limit (USL) and lower specification limit (LSL) can also be specified.
ALPHA = *n*	specifies an alpha value as level of significance to get confidence limits for various estimates.
SIGMA = *n*	specifies the sigma as process spread of the measurement parameter. If both sigma and tolerance (USL and LSL) are provided, it will give Precision-to-Tolerance for the measurement system.

Examples:

```
ESTIMATE / TOLERANCE = 40 ALPHA = 0.1 SIGMA = 5.15

ESTIMATE / USL=50 LSL=10 ALPHA = 0.1 SIGMA = 5.15
```

MSIGMA: Sigma Measurements

MSIGMA provides Defects per Million Opportunity and short-term level of sigma of a process assuming that you are providing long-term data.

Setup:

```
        * MSIGMA
HOT     *   MEASURE
```

For Multiple operations

```
        * MSIGMA
        *   USE
HOT     *   MEASURE
```

MEASURE command

MEASURE

MEASURE computes the level of sigma from DPMO and vice versa

/	UNIT = *n*	number of units observed.
	DEFECT = *n*	number of defects identified.
	OPPORTUNITY = *n*	number of opportunities for a product be defective.
	SIGMA = *n*	level of sigma of the process.

For multiple operations

The MEASURE command in multiple operations provides throughput yield of the process.

/	UNIT=*varname*	specifies the variable name for the units.
	DEFECT=*varname*	specifies the variable name for the defects.

SAVING: Loss/Saving

SAVING makes quality loss comparison between before and after beta correction adjustment.

Setup:

```
          * SAVING
          *    USE
               BEFORE
               AFTER
HOT       *    ESTIMATE
```

BEFORE and AFTER command

BEFORE *varname*	variables before the beta correction adjustment.
AFTER *varname*	variables after the beta correction adjustment.

ESTIMATE command

ESTIMATE

Estimates the loss per unit before and after implementation.

/ TYPE	specifies the type of quality characteristic.
SB	smaller-the-better type.
NB	nominal-the-best type.
LB	larger-the-better type.
TARGET=*n*	target value of measurement.
TOLERANCE=*n*	tolerance allowed in the measurement.
COST=*n*	cost of the defective product.
PRODUCTION=*n*	annual production in units.

For details in loss/saving see Taguchi's loss function (TLOSS).

TLOSS: Taguchi's Loss Function

TLOSS reports loss functions and Signal-to-Noise ratios depending on the type of quality characteristic.

Setup:

```
        * TLOSS
        *     USE
              LOSS
HOT     *     ESTIMATE
```

LOSS command

LOSS *varname*

Specify the variable name for the loss computation.

ESTIMATE command

ESTIMATE

Estimates Taguchi's Loss for the variable specified under different quality characteristic type.

/ TYPE	specifies the type of quality characteristic.
SB	smaller-the-better.
NBU	nominal-the-best :unilateral tolerance.
NBB	nominal-the-best :bilateral tolerance.
LB	larger-the-better.
TARGET=*n*	target value of measurement.
TOLERANCE=*n*	tolerance allowed in the measurement.

LTL=*n*	lower tolerance limit in bilateral tolerance.
UTL=*n*	upper tolerance limit in bilateral tolerance.
COST=*n*	cost of the defective product.
CRB=*n*	cost of the response below LTL.
CRA=*n*	cost of the response above UTL.

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